Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Pedal Operation by the Seated Operator.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 10-14, 1972	11	55

8a. CONTRACT OR GRANT NO. b. PROJECT NO. 7184 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) AMRL-TR-71-102 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Aerospace Medical Research Laboratory, Aerospace Medical Div., AFSC, Wright-Patterson AFB, OH 45433.

13. ABSTRACT

This paper attempts to serve three purposes:

1. To summarize the open scientific literature on muscular force applicable to pedals, and on the efficiency of foot motions on or between pedals depending on the body support and the body posture of the seated operator.

2. To discuss the applicability of such studies in automobile (or other equipment) design, especially to the design, selection, and arrangement of foot-operated controls.

3. To point out that for most conventional vehicles and equipment, modes of seating, and of pedal arrangement and operation follow largely common experience and tradition, and only partly scientific findings. For new man-machine systems, new solutions seem possible.

AD 733 315

DD FORM 1 NOV 65 1473

Security Classification

12

SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
Two Pennsylvania Plaza, New York, N.Y. 10001

Pedal Operation by the Seated Operator

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U. S. Air Force

SOCIETY OF AUTOMOTIVE ENGINEERS

Automotive Engineering Congress
Detroit, Mich.
January 10–14, 1972

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Pedal Operation by the Seated Operator

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EFFICIENT OPERATION of foot controls generally requires that the operator be seated. As compared to the standing position, sitting is more stable and requires less effort to be maintained; hence, sitting is less fatiguing and can be maintained for longer periods of time. Furthermore, the seated position allows simultaneous use of both feet, a requirement for most foot-controlled, man-machine systems. As the research reported in this paper shows, it is not sufficient merely to have the man sit; the type of seat to be used, that is, its modes and means of supporting the body, have to be carefully considered to allow an adequate body posture and performance. This is of special importance if adverse environmental factors such as vibrations or stochastic impulses interact with the task. However, the seat cannot be considered independently of the surrounding work-space (1)*; in particular, it must be matched to the type and arrangement of pedals to be operated by the seated person, and vice versa. The variables, body posture, body support, type of pedal, and the control task, interact among each other (and with other system characteristics) to determine the efficiency of operation of foot controls.

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SEAT, PEDAL ARRANGEMENT, AND SITTING POSTURE

The body posture of the pedal operator, and hence his efficiency in operating pedals, depends: on the type and size of his seat; on the number, type, size, and mode of operation of the pedal(s); and on the relative spatial arrangement of seat and pedal(s). Other factors like vehicle dynamics or vibrations in the man-machine-environment feedback loop also bear on the operator's efficiency, but will not be discussed here.

The most obvious relationships between seat and pedal are height and (lateral and sagittal) distance: A pedal arranged too far or too close, or displaced too much to the side, will impede or render impossible proper operation. However, even when located within easy reach, different arrangements of pedals are likely to be advantageous for, say, rare but forceful operations or continuous fine movements requiring little energy. Adjustability of the seat in height and distance will be required to accommodate operators of different body sizes, especially, with different leg lengths. Absence or presence of a backrest, its size and height above the seat pan can be important for the stability of the operator's body position—particularly if he has to apply considerable force to a pedal. Fig. 1 (from Ref. 2) identifies most important parameters of body posture and of body support during pedal operation. Thigh angle α, knee angle β, and foot angle γ determine pedal angle δ. These body position angles α, β, and γ in turn depend on

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3. To point out that for most conventional vehicles and equipment, modes of seating, and of pedal arrangement and operation follow largely common experience and tradition, and only partly scientific findings. For new man-machine systems, new solutions seem possible.

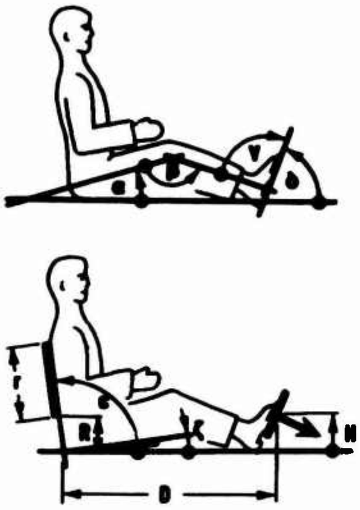

Fig. 1 - Leg angles and body support of seated operator of pedals (from Ref. 2)

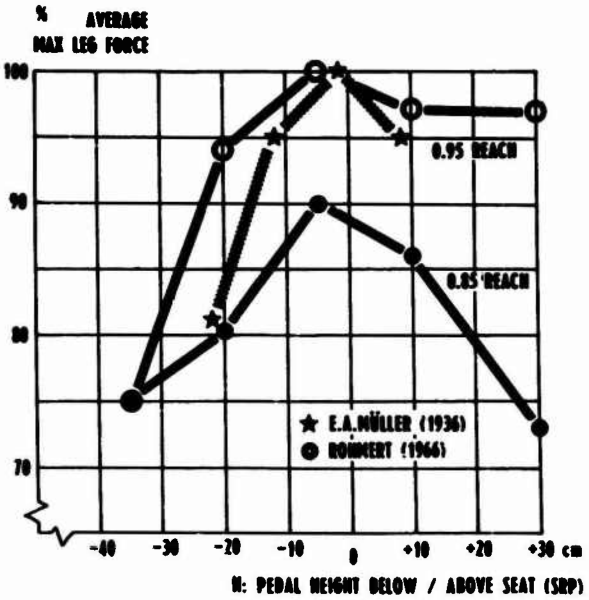

Fig. 2 - Maximal leg force applied to pedal at different pedal heights

the height of the pedal (H) and its distance (D) from the junction of seat pan and backrest tangents (seat reference point, SRP). Inclination of the seat pan and of the backrest are described by angles ζ and ϵ, respectively. Height of the lower edge of the backrest and the size of the backrest are indicated by the letters R and r. Not shown is the lateral displacement (L) of the pedal from the vertical plane dividing the seat into a right and left half.

This nomenclature will be used throughout this paper.

FORCES APPLICABLE TO PEDALS

The largest static forces that can be applied with one leg to a fixed pedal (without gross motion of pedal, foot, or leg) have been investigated by a number of researchers. From the very beginning, it was obvious that the seat-pedal relationships, that is, body support and body posture, especially knee angle, during the effort had considerable effects on the magnitude of force that could be applied. Previous publications (2, 3), contain detailed tables on the amounts and directions of forces exertable under a variety of conditions of body posture and body support. Hence, only the principal effects of sitting posture and pedal design and arrangement on force application will be discussed here.

Forces applicable to aircraft pedals were of interest as early as 1930 when Hertel (4) used a Junkers aircraft mockup to measure the leg strength of 11 engineers and pilots. The mean forces fell almost 70% from 2000 N* to about 600 N when the subjects were fatigued after sustained force exertion. In 1936, Gough and Beard (5) showed that the mean force decreased about 15% from 1900 to 1600 N when the pedal was lowered from 15 to 30 cm below seat level. Elbel (6) measured average forces of almost 2600 N at B-24 aircraft pedals, when the subject's knee angle β was about 110 deg and the angle γ between the lower leg and the pedal about 120 deg. As late as 1953, however, Crawford (7) reported that the pedal assembly of a taxiing aircraft was broken by the pilot, who obviously had applied more than the mere 2200 N until then officially specified as the maximal design load. Crawford cites subsequent tests with 10 pilots showing forces up to 4450 N applied to aircraft pedals.

Forces exertable at a pivoted pedal were measured by Müller (8). He was the first and apparently, until 1971, the only researcher to publish such strength data of (two) women in addition to the scores achieved by one man. Müller found considerable interindividual strength differences between his subjects. The two women were much weaker than the male subject. Regardless of the absolute scores, each subject could exert his individual maximal force when the pedal was in front of the hip joint, at about seat height, and so far away that the knee angle α had to be at least 130-150 deg to reach the pedal (Fig. 2). The force was diminished if the seat had no backrest, or if the pedal was moved forward, backward, or laterally, or lowered from its position in front of the hip joint. Müller found that the maximal force could be transmitted to the pedal with the instep of the foot over the pedal axis, and that there are no gross strength differences between the right and left leg.

Hugh-Jones (9) also used a pedal pivoted near the instep, approximately in line with the axis of the tibia. He found that his subjects (six "powerfully built men") could exert largest forces on the pedal when the knee angle was about 160 deg (Fig. 3). As in Müller's experiments, the largest force could be exerted when the pedal was located in front of the hip joint. In this position, Hugh-Jones observed no gross differences in the strength of 32 drivers of the Royal Armoured Corps and of 16 London schoolboys, aged 14-18 years whom he used as subjects in addition to his original six. Hugh-Jones' data showed that seemingly small changes in knee or hip angle may

*Newton, 1 N $\approx$ 0.225 lb.

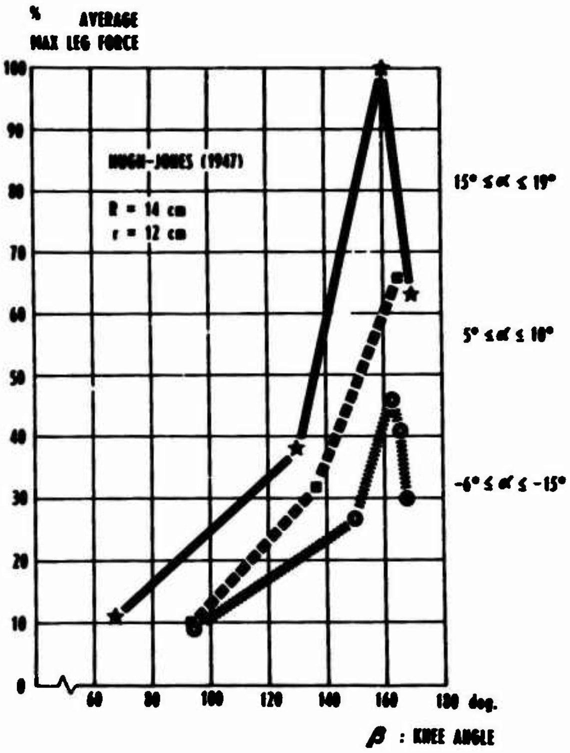

Fig. 3 - Maximal leg force applied to pedal at different knee angles

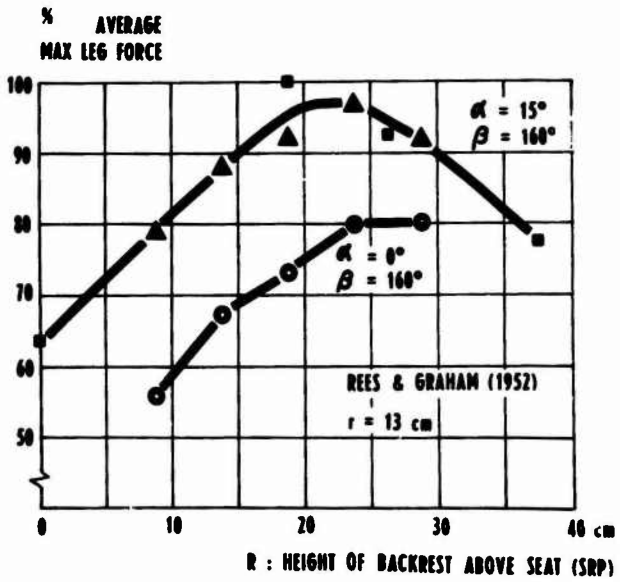

Fig. 4 - Maximal leg force applied to pedal with different backrest arrangements

bring about rather large changes in the forces applicable to the pedal.

Rees and Graham (10) had their pedal pivoted under the ball of the foot; the axis of rotation seems to have been about 2.5 cm below the surface of the pedal. Twenty men pushed at the pedal with the ball of the foot. Rees and Graham found the position of the backrest of the seat to be an important factor on the force that can be exerted (Fig. 4). Their data also showed again how the force applicable is reduced when the

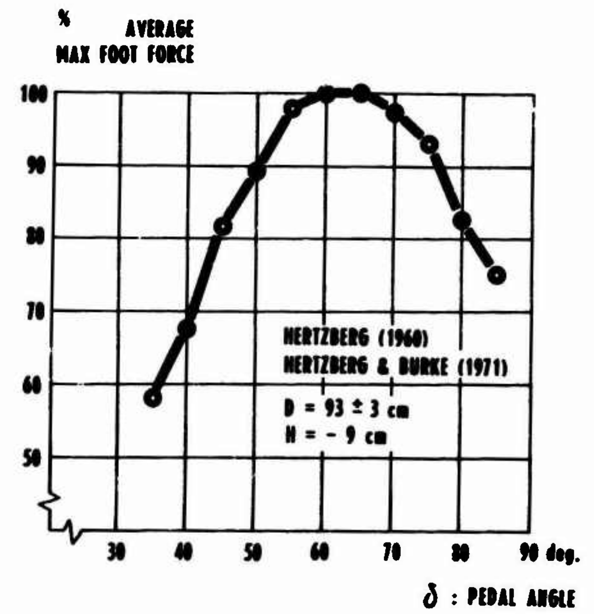

Fig. 5 - Maximal foot force achieved in attempted foot rotation at different pedal angles

pedal is lowered from the height of the hip joint to a location well below the seat pan.

Martin and Johnson (11) used a pedal pivoted close to the subject's shin. When the pedal swung into the line of thrust, the axis interfered with the subject's leg if the pedal was close to the seat. Therefore, distance less than 73 cm could not be tested. The 166 subjects pushed with the ball of the foot. Martin and Johnson found largest forces when the pedal was at approximately the height of the hip joint, and at the rather short distance of only 80-90 cm in front of SRP. Thus, with this special pedal arrangement, highest forces could be applied with the legs flexed.

Rohmert (12) measured the forces that 60 men could exert on a fixed pedal with the ball of the foot (Fig. 2). The results showed once more the decrease in exertable forces when the pedal was arranged so close to the subject that the knee must be bent severely as compared with the force exertable when the leg is almost straight and about horizontal. In 1971, Rohmert and Jenik (13) found that if the pedal was at about 95% of the reach distance of the foot, women could exert only about half as much force as men; however, at 90% reach, they exerted four-fifths of the men's force. Including even shorter arrangements, the mean ratio of female/male pedal force was the "classical" two-thirds.

So far, forces were discussed that can be exerted in static thrust of the total leg, that is, accomplished by attempted changes in the knee and hip angles. Fig. 5 however, presents results of Hertzberg's experiments in which the subjects exerted static force in attempted plantar rotation of the foot about the ankle joint (14, 15). Such rotational foot forces were found to depend on the pedal angle δ, that is, on the angle γ between lower leg and foot. These foot rotation forces are, of course, much lower than the forces exertable in total leg thrust.

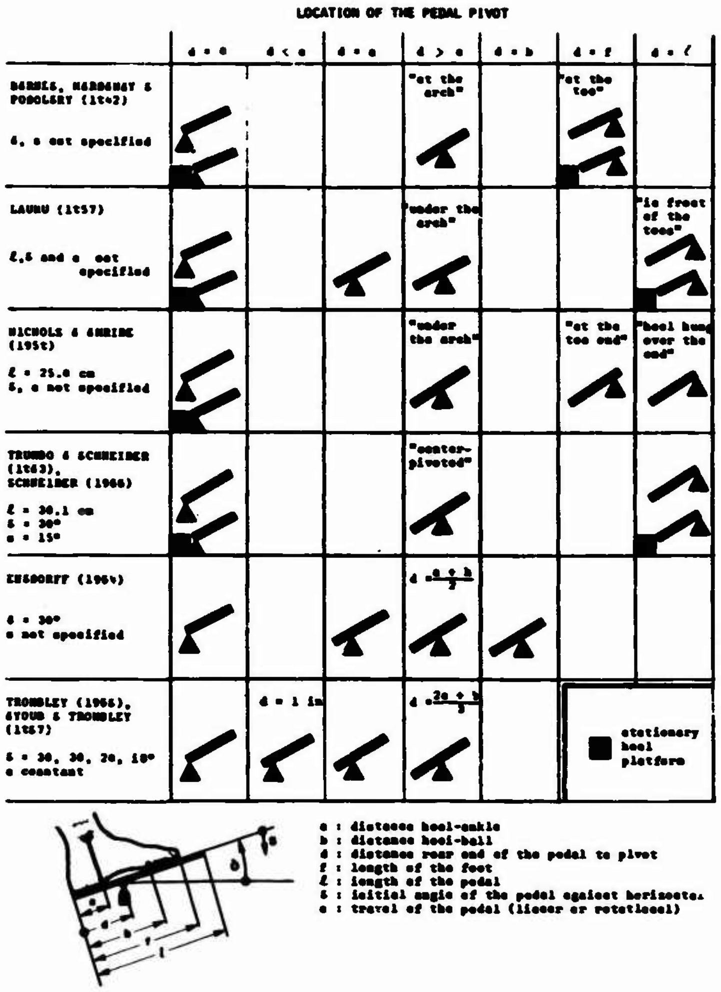

Fig. 6 - Pedal variables researched in six studies (from Ref. 2)

REMARKS - Despite the rather large number of published data, it is often difficult to assess and compare the published data on forces exertable to pedals, mainly for the following reasons:

1. The experimental setup is not always completely described. What, for example, were the design and the arrangement of seat and pedal in the "aircraft" experiments? Can the hip and knee angles in one study be related to distance and height adjustments of the pedal in another study?

2. The instructions to the subjects are often not reported. Rees and Graham told their subjects to increase the force gradually and to hold the greatest push for a few seconds; Rohmert and Jenik say the muscle contraction lasted about 1 s. How did the subjects in other studies exert their strength? Did they get an immediate feedback of the attained force? Did they compete against each other, as in Hugh-Jones' experiments?

3. The score or index the experimenter selected as maximum generally was not stated. Was it an instantaneous peak amplitude of the force curve? Was it a mean force, averaged over some period of time? Was it an average of several trials, as in Rohmert and Jenik's experiments?

Kroemer (16) and Kroemer and Howard (17, 18) pointed out that these and other experimental conditions may greatly affect the results of strength measurements

A final comment concerns the applicability of maximal static strength data to conditions that require either submaximal or dynamic efforts from the operator. Kroemer (16) elaborated on that physical as well as physiological reasons speak against the relevance of maximal static data for any other but this mode of muscular exertions. Hence, the data cited should have their largest value for equipment and vehicles that do require large static forces in pedal operation.

SPEED OF OPERATION OF PEDALS

A particular group of pedals, sketched in Fig. 6 (from Ref. 2), has served in a series of experiments conducted by six groups of researchers. All the pedals had in common that they were rotated with the foot about a pivot near the pedal surface. This pivot was located at the rear end of the pedal, or at the front, or somewhere in between.

Barnes, Hardaway, and Podolsky (19) were the first to study operation of these pedals. Fifteen sitting subjects depressed each pedal with the right foot continuously as fast as possible during a period of 3 min. Hinging the pedal at the rear or at the front allowed subjects to perform the largest number of (attempted and completed) strokes per minute. Using stationary platforms for the heel of the foot, or hinging the pedal "at the arch" of the foot reduced the stroke frequency.

Lauru (20) had in addition one pedal with the pivot "in the axis of the tibia" under the heel. He measured the forces exerted on the pedals and the time consumed in their operation. The pedal hinged under the heel could be activated fastest and required least force for operation by a sitting subject. The pedals hinged "under the foot arch" and at the rear end were the next best, while the front-hinged pedals needed most force and time for activation.

Nichols and Amrine (21) attached weights of 5, 10, and 15 lb to Barnes' pedals through cables and pulleys, thus creating three levels of resistance. Five subjects operated the pedals while standing. The smallest increases of the subjects' heart rates occurred when the pedals were hinged either at the rear or at the front end.

Trumbo and Schneider (22) also used Barnes' pedal types. From the initial position of 30 deg, the pedals had to be pressed down 15 deg against a spring, requiring work of about 0.16 J*. Ten sitting subjects operated the pedal as fast as possible upon a light signal. Discrete activations were required. The response times (reaction plus motion time elapsed until the pedal was depressed 15 deg) were smallest with the pedals hinged at the rear, and largest with the pedals pivoted at the front.

Ensdorff (23) had eight subjects sit on a chair, their thighs horizontal, their shins at angles of 90, 100, 110, or 120 deg with the pedal surface in the initial position–30 deg over horizontal. Four different levels of pedal resistance were employed. Upon a light stimulus, the subjects depressed the pedal as fast as possible to move a pointer 7.5 cm to a fixed mark. Ensdorff measured reaction time (from the onset of stimulus to beginning of pedal motion), travel time of the pedal, and deviation of the pointer from the goal mark. Reaction time was shortest with the pedal hinged at the rear. Travel time was shortest with the same rear-hinged pedal and increased with more anterior pivots.

Trombley (24, 25) had 15 seated subjects depress hinged pedals in discrete movements as fast as possible to a fixed stop. The stop was adjusted to require travels of 12 deg or, respectively, of 1.9 cm at the ball of the foot. Work of 0.5-2.1 J was necessary to move the pedals. In the starting position, the subject's thigh was horizontal, the knee at 114 deg, the angles between tibia and pedal were 78, 84, 90, or 96 deg. The system was balanced so that the starting position could be maintained without muscular effort. Trombley found:

1. Reaction time - Reaction time was independent of the location of the pivot, but increased with increasing resistance of the pedal. It was shortest with an initial angle of 78 deg between tibia and pedal, and increased linearly with increasing initial angles. These findings held true both for constant travel distance and constant travel angle.

2. Travel time - Through a constant 12 deg, it was largest with the rear-hinged pedal and decreased linearly with more forward pivot locations. However, the time to travel a constant 1.9 cm at the ball of the foot was shortest with the rear-hinged pedal and increased when the pivot was located more forward. Travel time was shortest with the smallest pedal resistance and increased with larger loads. Travel time was somewhat irregularly related with the pedal-tibia angle, but seemed to be shortest with the smaller angles. Travel through the constant angle of 12 deg was faster than through the constant distance of 1.9 cm at the ball.

Konz et al. (26, 27) reported on nine experiments with an automobile pedal combining brake and accelerator controls. This pedal is supported by two shafts perpendicular to the pedal surface. Pressing down the front part ("accelerating") moves the anterior shaft down, the pedal then pivots about the hinge attaching it to the posterior shaft; pressing down the rear end–the posterior shaft ("braking")–causes the pedal to pivot about the hinge attaching it to the anterior shaft.

In the first series of experiments, Konz and coworkers found brake actuation starting from the depressed accelerator considerably faster with this dual pedal than with the conventional two-pedal arrangement. Subsequently, a variety of design features of the combination pedal was investigated, such as pivot location, initial pedal angle, angular travel of the pedal, actuation forces on brake and accelerator parts, horizontal and vertical distances between pedal and seat. Based on their experimental findings, Konz et al. (27) give detailed design recommendations for the dual-function pedal; for example, the pedal should be at 30-40 deg above horizontal, the brake resistance should be about 58 N, and the accelerator resistance about 27 N.

REMARKS - The pedal types first used by Barnes and coworkers have been the object of research of a rather large number of studies. However, there are basic differences among the studies: Seated or standing subjects, continuous or discrete operation, differences in pedal design, resistance, etc. Table 1 (from Ref. 2) lists most of the experimental parameters. This table in combination with Fig. 6 shows that the pedal designs used, the actions required, and the rating criteria applied are not consistent among the studies. Hence, there is some desirable overlap in the studies, but several experimental parameters are not sufficiently covered.

The combination pedal studied by Konz and coworkers was specifically developed for use in automobiles. Implementation of well-defined design parameters should yield certain desirable improvements, mainly in speed of activation. However, the researchers caution in their final statements (27) that other designs should be considered which, obviously, could have additional and/or different advantages for automobile driving.

MOVEMENTS BETWEEN PEDALS

The time consumed in moving one's foot from one location to another can be a critical factor in emergencies, as in the case of the automobile driver who has to move his foot quickly from the accelerator to the brake pedal. In most of the cited studies on hinged pedals, the reduction of reaction and travel time was among the experimental variables assessed. Therefore, these studies have some bearing on the time consumed in motions to or between pedals, and their activations. Konz

*Joule; 1 J ≈ 0.738 ft-lb.

Table 1 - Experimental Variables in Six Studies on the Speed of Operation of Hinged Pedals (from Ref. 2)

	BHP	L	NA	TS	E	T
Subjects						
Sample population	?	?	X	X	?	X
Males	X	?	X	X	?	X
Females	X	?	–	–	?	–
Thigh angle	?	?	?	?	X	X
Knee angle	?	?	?	?	X	X
Tibia-pedal angle	?	?	?	?	X	X
Sitting	X	X	–	X	X	X
Standing	–	–	X	–	–	–
Pedal						
Length	X	?	X	X	X	–
Breadth	X	?	X	X	X	–
Pivot location	X	X	X	X	X	X
Initial position	?	?	?	X	X	X
Initial balance	?	X	X	?	?	X
Force, etc., necessary	?	X	?	X	?	X
Action required						
Travel to mark	–	?	?	–	X	–
Travel to stop	X	?	?	X	–	X
Travel given angle	?	?	?	X	?	X
Travel given distance	?	?	?	–	?	X
Discrete motions	–	?	?	X	X	X
Repetitive motions	X	?	?	–	–	–
Rating criteria						
Force, work, etc.	–	X	?	–	–	–
Number of operations	X	?	?	–	–	–
Reaction time	X	?	?	X	X	X
Travel time	X	X	?	X	X	X
Accuracy	–	?	?	–	X	–
Physiologic strain	–	–	X	–	–	–

X: specified by the author. ?: not specified. –: not applicable.

and coworkers' studies (26, 27) of a combined accelerator-brake pedal aimed directly at reducing the time needed to initiate the braking motion after the foot had been depressing the accelerator. Several biomechanicists such as Hindle et al. (28) and Coermann and Kroemer (29) had suggested that the direction of the foot motion could have significant effects on the motion time; especially, that "sliding" motions (including mainly the foot and the lower leg) may be faster and more accurate than "lifting" actions (involving major displacements of the thigh also).

Tejmar (30) reported on an experiment with 29 male subjects who moved their right feet as fast as possible from a central start position to target buttons located on a circle (13 cm radius) around the start button. On the circle, the targets were at 45 deg intervals, but with the forward (0 deg) and backward (180 deg) positions omitted. The targets were either at the same height as the start position, or lowered or raised by 6.5 cm. Start and target buttons were mounted on a board which could either be arranged horizontally, or tilted 45 deg toward the subject.

The subject sat on an upholstered chair, with the right foot resting on the start button. In this position, his thigh angle α was 10 deg, his knee angle β at 110 deg. Upon a signal, he brought his foot to a predetermined target as quickly as possible. This motion was repeated 50 times. After 10 min rest periods each, 50 motions to two other targets were performed. The next test session with three times 50 motions to other targets took place the next day or later. The sequence of target locations was at random.

A preliminary analysis of the recorded travel times showed that the subjects did not reach a level of performance. Among the motions, those "downhill" or to a target at the same height as the start position seemed to be a little faster than those "uphill." No clear effects of the directions of motions (45, 90 deg = left, 135, 225, 270 deg = right, 305 deg) were apparent. However, any such statements must still be regarded as tentative, since the final data analysis has not yet been published. Nevertheless, the fastest times observed in Tejmar's study of about 100 ms for most conditions agree with the travel times registered by Kroemer (2, 3).

Kroemer conducted experiments to measure the travel time and to check the accuracy of discrete motions of the right foot. Seated subjects moved their feet between circular targets arranged in: sagittal columns of three on a circle segment (57.5 cm radius) around the knee joint; or in lateral rows of three, with a distance of 15 cm between target centers. The motions, always to the adjacent target, required that: in the sagittal motions (fore-aft), the knee angle β be altered in 15 deg increments between 90-150 deg; in the lateral (left-right) motions, the lower leg be tilted 15 deg to either side of a vertical plane at each knee angle. The thigh angle α-0 deg was not changed appreciably in either the sagittal or lateral motions. The motions were allotted in a stratified random order to the 20 subjects participating so that each subject worked on the same two lateral rows and two sagittal columns of three targets.

Each subject was instructed to move his foot, at a time of his choice, from the center of the target to the predetermined goal target. Motion time and segment hit recorded, the subject would assume the center position on this target and move to the next one, etc. The subject did not look at the targets, but did get immediate feedback on time and accuracy of the foot motions. No minimum number of feet motions was prescribed, but each subject was trained until his travel times reached a steady level, judged by the five shortest motion times achieved during each test session between the same targets.

Based on these five fastest motions, the following results were obtained: the mean travel times lay between 83-110 ms. Within this narrow range, it was significantly faster to move the lower leg fore and aft between knee angles β of 90, 105, and 120 deg, than to move the lower leg elevated to 150 deg backward or sideward. Within lateral motions, no statistically significant differences in travel times were found. No trends were observed between direction or location of the motions, and the number of times certain segments of the targets were hit.

REMARKS - The studies on the time consumed in foot movements point out certain directions, or travel distances, or

certain arrangements of separate pedals that allow fast operation. The studies conducted seem to indicate that the more complicated motions take most time: "complicated" either in the sense that large leg masses must be accelerated or decelerated in lifting the total leg, or in tilting the thigh with lower leg and foot attached, or that obstacles must be avoided in the course of the movement (like the start button in some of Tejmar's experiments, or the rim of the steering wheel or the edge of the adjacent pedal in some automobiles). It seems to be biomechanically advantageous (but has yet to be proven experimentally) that moving the smallest possible mass about the nearest joint should result in fastest and best controlled motions: for example, either moving the lower leg (and foot) fore and aft about the knee joint, or better, tilting the foot laterally about the heel resting on the floor, or rotating the foot about the ankle joint, as approximated by many of the "combination pedals" patented or proposed in the literature.

ACCURACY AND EFFICIENCY OF PEDAL OPERATION

Certain criteria of the accuracy of pedal operation were part of several of the studies already cited: In Barnes' et al. studies, it was registered whether the pedal was either fully or only incompletely depressed. Ensdorff had his subjects move a pointer to a mark by depressing a hinged pedal; he found that the smallest deviations from the goal were achieved with the pivot of the pedal under the ankle or the arch of the foot. Konz and coworkers' road experiments with the combination pedal, aimed primarily at assessing reaction time, imply necessarily that this control allowed an operation accurate enough to actually drive a car. In Kroemer's study, the targets had at least to be hit at all with the foot in order to measure the time; in about 10% of the trials, the subjects did not hit the target within 500 ms, which was counted as a miss. Kroemer analyzed his data to find out whether or not there were differences among foot motions in the frequency of missing or of hitting either the center of the target or the ring, or of hitting those segments of the ring closest to the starting point of the motion, or segments in the direction of motion, etc. Kroemer could not detect any such differences either within lateral motions of the foot, or within sagittal movements, or between the lateral and sagittal motions. The no-difference verdict applied both to the fastest and to slower motions.

Corlett and Megaw (31) investigated the role of kinaesthetic and visual feedback on very small foot motions. Sixteen sitting subjects placed their right feet on a pedal pivoted under the ankle.

Their task was to "make minimal voluntary motions" with the pedal. The torque at the pedal was set to either 0.4, 1.3, 2.2, or 3.01 N·m*. The amount of pedal motion, achieved by plantar flexion of the foot, was displayed to the subject on an oscilloscope with the travel amplified by factors of 1/4, 1, 4, and 16. Under each of the experimental conditions, the subjects made the required 30 movements in approximately 20-25 s. Changing the torque did not significantly affect the mean minimal movement of about 0.2 deg. Increasing the visual gain (the amplification factor) from 1/4 to 16 enabled the subjects to reduce the mean minimal motion to about 0.1 deg.

Drury (32) reported on experiments in which the subjects tried to make the smallest foot movement they possibly could. In the first experiment, six male subjects were seated 35 cm higher than the level of the pivot of a rear-hinged pedal. The pedal was at an angle of 45 deg with the horizontal. Inertia and torque of the pedal were "at three levels, low, medium and high." Upon signals by the experimenter, the subject made discrete toe-down movements under each condition. In the second experiment, with 18 male subjects, each operator sat so that his thigh was horizontal and his lower leg vertical. The pedal, pivoted at the axis of the ankle, had its initial positions at 15 deg above, at 0 deg, and at 15 deg below horizontal. In each position, the subject performed 50 self-paced toe-down motions against a constant torque of approximately 4 N·m. Drury concluded that the subjects could voluntarily perform extremely small motions. The mean amplitude of the motions was about 0.8 deg in the first experiment, and about 0.2 deg in the second experiment. Inertia, torque, and initial position did not significantly affect the amplitudes.

Very few experiments have been reported comparing tracking performance with hand and foot operated controls. Grether (33) caused a pointer of an Autosyn indicator to oscillate irregularly. Using a stick or a wheel control (from a Link trainer) or rudder pedals (from a P-47 aircraft), subjects had to try to hold the pointer on a fixed mark. The stick was moved with the preferred hand laterally or fore and aft. The wheel was grasped with both hands and either rotated or moved fore and aft. The right and left rudder pedals had reciprocating fore and aft movements; resting the heels on the floor was permitted. Efficiency (accuracy) of tracking was measured as the time during which the pointer was actually kept on the reference mark.

In the first series of experiments, the maximal control travels necessary to keep the pointer on the mark were 10 cm at the pedals, 20 cm at the stick, 20 cm of fore and aft motion, and 28 cm rotation at the wheel. During 5-min trials with 24 subjects, average time-on-target accomplished with the pedals was 52% of total time which is (statistically) significantly less than the 55-61% achieved with stick and wheel.

In a second series with the pedals and the stick, the amount of travel of both controls was equalized to 10 cm. Thirty-six pilots performed six 2-min tests with each control. The on-target time was 56% for the rudder pedals, 60% in lateral stick motions, and 68% in fore-aft stick motions.

In a third series of experiments, only rudder pedals were used. The maximal travel necessary to keep the pointer on target was again 10 cm. The same 36 pilots as before were seated with knee angles β of either 105, 120, or 135 deg, respectively. No differences in tracking accuracy (about 60% on-target time under all conditions) were found to be connected with the knee angles, but the subjects felt that 120 deg were most comfortable.

*Newton-meter, 1 N·m ≈ 0.738 ft-lb.

Jenkins (34-36) reported on the "consistency" achieved in applying static forces to rigid aircraft controls–sticks, wheels, and rudder pedals. Twenty subjects had to apply predetermined forces of between 4.5-280 N as accurately as possible to the controls. The rudder pedals were "worked from the ankle" with the heels resting on the floor. Generally, too much force was applied if small force was required, and too little was exerted if large force was requested. "Consistency" of force application was expressed in terms of the standard deviation of the force exerted divided by the force level required. Consistency was least at the small force levels and best at the higher force levels. Jenkins found that the "relative accuracy of performance with the feet was approximately the same as . . . with the hands, but that differences in the apparatus may be related to this finding."

REMARKS - Research on the accuracy of pedal operation, reported in the open literature, covers a limited number of experimental variables. However, this research does really not explain how we manage to accurately operate the rudder pedals in aircraft, to regulate the speed of a sewing machine with a foot controller, or how we manage to press the buttons for windshield washer and high/low light beams, operate the clutch, and accelerate and decelerate the automobile with our feet. Hence, very little information can be drawn from the literature with regard to improved efficiency of operation to be achieved by differently designed foot controls. Coermann (37) pointed out a number of possible solutions, but his death prevented the completion of experiments initiated to assess their respective advantages. Woodson and coworkers (38) also mention a number of possible solutions.

SELECTION AND ARRANGEMENT OF PEDALS

In man-operated vehicles, man is the crucial component determining the total system output. By proper control operation, the driver has to adapt the vehicle dynamics (actual heading, speed, etc.) to the forcing functions (such as road layout, desired speed) and to disturbances (wind blast) or other environmental conditions. Man is the primary mover in this complicated feedback system, parts of which are depicted in Fig. 7. The system output, success, or failure of the mission, depend on the operator's ability to join adequately forcing function, disturbances, and vehicle dynamics. His means of affecting the system are manual controls and the foot-operated pedals.

Selection and arrangement of the controls has to be implemented in accordance with the layout of the total system, with primary concern for man's anthropometric, biomechanical, and ergonomic characteristics. Assessment of these operational parameters is schematically indicated in Fig. 7, and, with respect to pedal operations, has been discussed in the foregoing sections of this paper.

The findings may be summarized as follows:

If very large static forces are to be exerted, the pedal should be at about seat height, in front of the seat, and at such a distance that the leg is almost straight when the foot is placed on the pedal. When large forces are required, the operator must

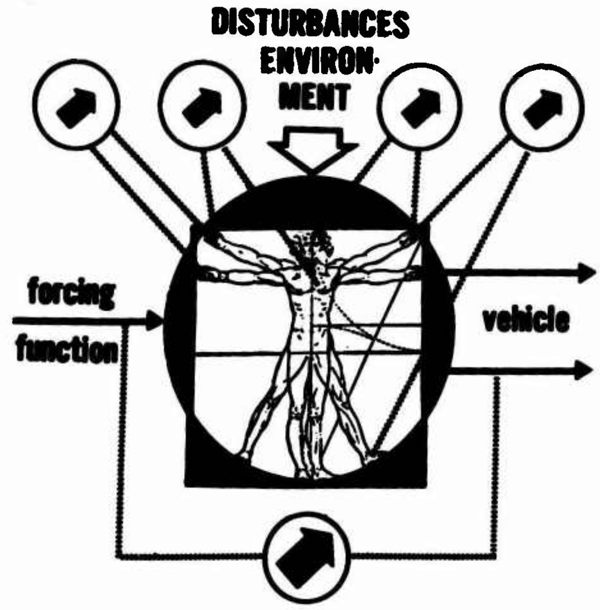

Fig. 7 - Human operator as prime mover (controller and effector) in man-vehicle system

have a backrest to lean against; his thigh should be horizontal or inclined with α up to 30 deg, the knee angle β between 150-165 deg, and the angle γ between tibia and foot between 80-90 deg.

If only small forces are required, the pedal may be lowered; force then may be exerted either by thrust of the total leg or by rotation of the foot about the ankle. For small forces, or for continuous steering tasks, or for discrete activations, the thigh should be horizontal or slightly elevated with $0\text{ deg} \leq \alpha \leq 15$ deg; the knee angle β could be anywhere between about 90-150 deg, and the foot angle γ between 90-120 deg.

The rather large number of experiments on the speed of operation (either discrete or continuous) with certain pedal designs does not cover all aspects. Hence, any conclusions that may be drawn from the research results published depend on how well the actual conditions of design and operation coincide with those prevailing in the experiments reported. With this note of caution emphasized, the studies on speed of pedal operation seem to indicate that a pedal hinged at, under, or near the heel of the foot allows fastest activation. As far as the speed of foot motions between separate targets is concerned, the literature does not offer any clear preferences. While it is true that, say, lateral motions of the elevated lower leg may be slightly slower than fore and aft motions of the vertical lower leg, or that sliding motions of the foot might be faster than lifting actions, there is at present not enough evidence to suggest an according redesign of our current automobiles.

Motion stereotypes by now firmly established in the driver population, and a variety of biomechanical considerations speak against many conceivable small-scale rearrangements of the pedals in otherwise conventional vehicles. However, a radical redesign of foot controls may have significant advantages over the current uses. Combination pedals like the interlocking brake-accelerator pedal do warrant further investiga-

tions. A host of even more exotic design possibilities lends itself to further exploration. It does not only include new combinations of the old tasks of clutching, braking, and accelerating, but might include steering as well (or instead). As the literature indicates, assumed advantages of hand controls over foot-operated controls are not very clearly supported by experimental evidence, and may be decisively dependent on the nature of the controls, and the total system characteristics. In some contrast to conventionally biased expectations, highly complex and sensitive even vital control operations are executed with the feet in current systems. This is the case with industrial equipment such as cranes, household sewing machines, automobiles, aircraft, and space systems.

A radical redesign of foot-operated controls would be most likely (and be most easily accepted by the public) in combination with really new concepts of individual vehicles or mass-transport systems. A discussion of the feasibility of such new vehicles is beyond the scope of this paper. However, the combined results of growing population, increasing awareness of possible damage to ecology and human life may bring about a rather thorough reassessment of our current design principles, and adaptation of new ones, better fitted to man's needs and capabilities.

A number of human-engineering guides imply or contain statements that (except for application of large force) foot-operated controls be less desirable than hand controls (28, 29, 39-55). After rather carefully checking the original research papers available, this author now concludes that very little evidence (if any) can be found in the primary literature to support (or discredit) the generalized opinions so convincingly repeated in the secondary literature about the advantages or disadvantages of foot- versus hand-operation of controls. The scientific literature covers only a limited number of pedal parameters with respect to selection, design, arrangement, and operation. Obviously, the current usages of foot-operated controls in private vehicles, mass transportation systems, in agricultural or earth moving equipment, in cranes and other man-controlled systems rely, to a large degree, on experience and tradition.

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Society of Automotive Engineers, Inc.
TWO PENNSYLVANIA PLAZA NEW YORK N Y 10001

12 page booklet. Printed in U.S.A.